HI-stacking predictions for upcoming surveys with SKA precursors

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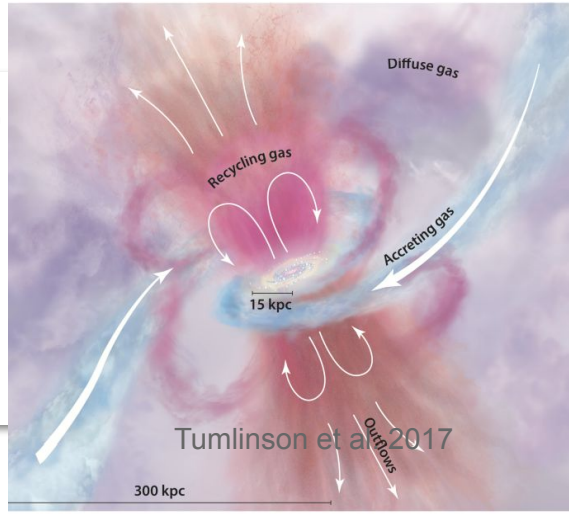
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Introduction

Galaxy evolution is regulated by continuous cycle of gas (HI+H_2) accretion, consumption and feedback. **How does the HI behaves at z > 0.25?**

Neutral Hydrogen : **HI gas is the raw fuel for the star formation**

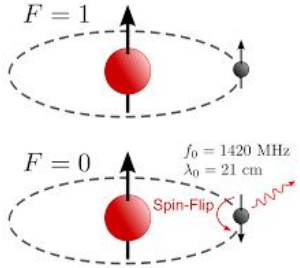
- **21 cm line is a good probe but very weak.**
- **It's hard to detect at z >0.2 directly.**



21-cm line detection:

(1) Direct detections with SKA precursors ASKAP, MeerKAT etc.

(2) HI-stacking at known redshifts—> Statistical properties z>0.2



In this work, we make predictions for two surveys: MIGHTEE-HI and WALLABY.

- Observables : Number of direct detection, average HI mass(stacking).
- We explore the sensitivity of the HIMF against these mock observables.
- We also simulate joint optical-HI signal for survey sensitivity: Joint Catalog

- We constrain the HIMF with these observables and plan to estimate conditioned HIMF based on color and luminosity.

HI-Surveys: MIGHTEE-HI and WALLABY

Table 2. Key parameters of the MIGHTEE-HI observations

Area covered	32 deg^2
Frequency range	900–1420 MHz
Redshift range for H I	$0 < z < 0.58$
Nominal angular resolution	12 arcsec
Velocity resolution	5.5 km s^{-1} (1420 MHz)
Per channel flux sensitivity	100 μJy beam^{-1} (1420 MHz)
Column density sensitivity (22 km s^{-1})	2.6×10^{19} cm^{-2}

N. Maddox et al. 2020





Parameter	Value	Unit
maximum baseline	2	km
angular resolution (at $z = 0$)	30	arcsec
sky coverage	$-90°$ to $+30°$	
number of ASKAP pointings	1200	
integration time per pointing	8	hours
total observing time	9600	hours
frequency range	1130 – 1430	MHz
redshift range	0 – 0.26	
velocity range, cz	$-2,000$ to $+77,000$	km/s
bandwidth	300	MHz
number of channels	16384	
frequency resolution	18.3	kHz
velocity resolution	3.9	km/s
rms sensitivity (for $T_{sys} = 50$ K, 0.1 MHz)	0.7	mJy
Column density sensitivity, N_{HI} (0.1 MHz)	1.7×10^{19}	cm^{-2}

WALLABY

WALLABY webpage

- **MeerKAT** has a single-pixel feed with 64 G-dishes of size 13.5 m. FoV ~ 1 deg^2
- **MeerKAT's** early science observations with of two fields have been done and data is publicly available (reduced and data cubes generated).

- **ASKAP** has 36 antenna with PAF , FoV ~ 30 Deg^2.
- **ASKAP** has completed phase-I and II pilot survey observation 180 deg^2 each.
- Combination of these two surveys can probe HI-gas in different depth and environments.

Mock HI Catalog:

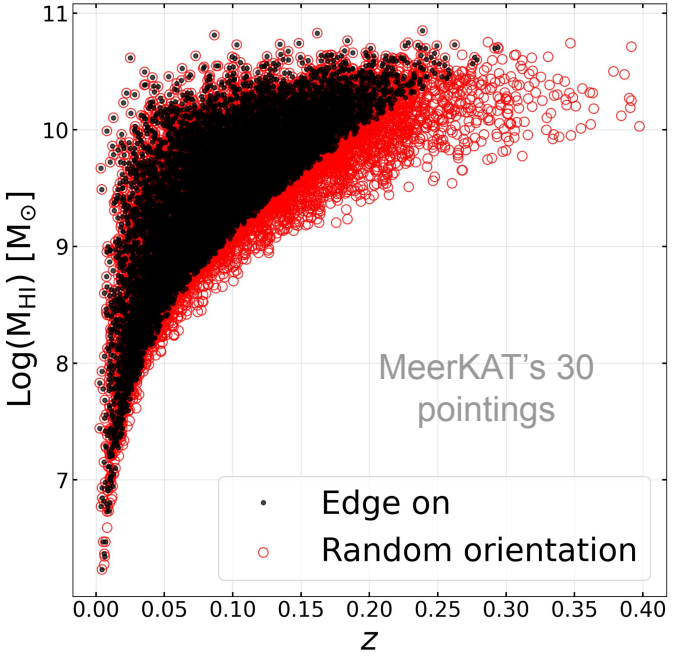
- Our approach is simple and unique to build mock observing cone unlike the other approach in which N-body simulation and halo based models etc. are used.

- In this approach , we randomly distribute galaxies in a cone with redshifts and HI-masses using HIMF (z =0) and relative volume respectively. No clustering

- Other quantities like size of HI disc, linewidth are scaled with HI mass.

- We use optimal sensitivity (effective no. of baselines) of instruments where the source are just unresolved.

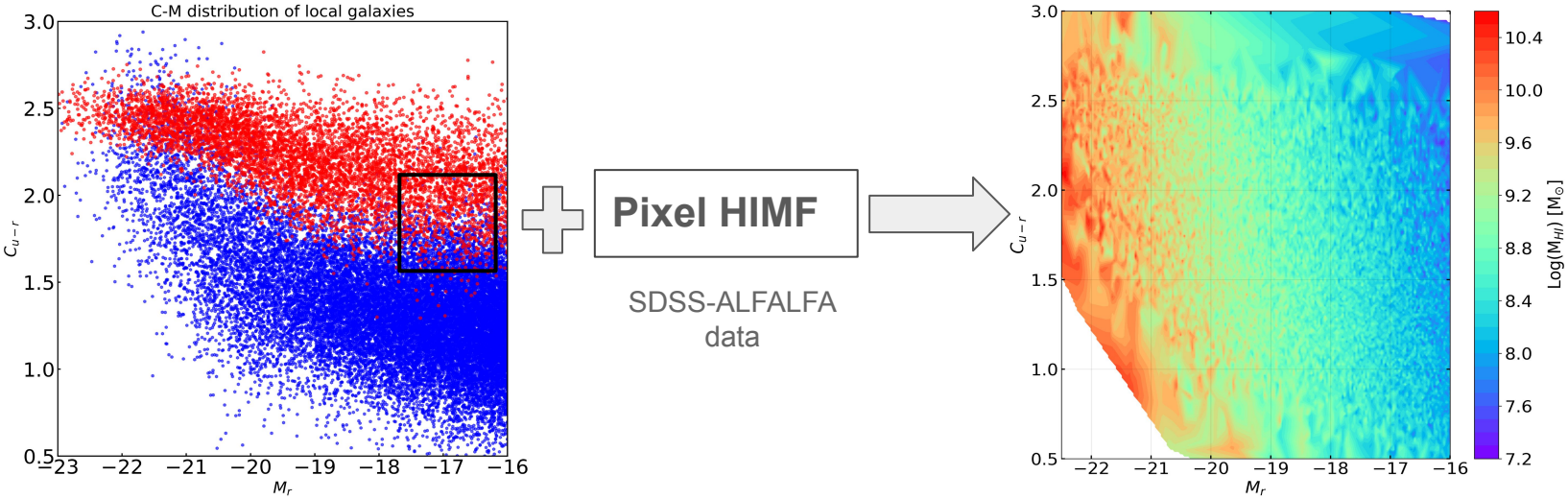
- We also account random inclination effect in our approach that leads to the increased number counts in HI-detections.



Joint HI-optical Catalog:

We also simulate HI-optical properties (r-band mag, u-r color,HI mass) of the galaxies. We use SDSS-ALFALFA common volume data (DR7) as template.

- Estimate HIMF for different regions(pixels) in color magnitude plane.
- Simulate bimodal (u-r,Mr) distribution from SDSS spectroscopic survey.
- Use pixel-wise HIMF from SDSS-ALFALFA common volume data to assign the HI-mass for same pixel to galaxies in MeerKAT's FoV.
- Final catalog has HI-optical properties with spectra of HI-line (HI-line profile)

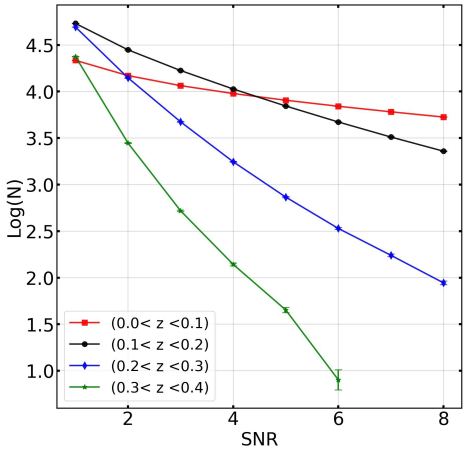


Reproduced from Baldry et al. 2004

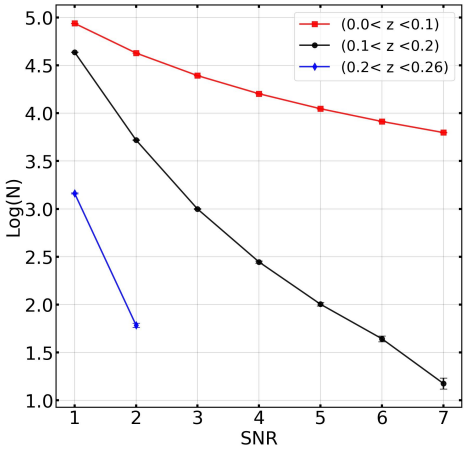
Results: direct detection and resolution map

- In final catalog, we count sources with SNR > 5 as direct detections.
- We also make resolution maps to count number for different SNR.

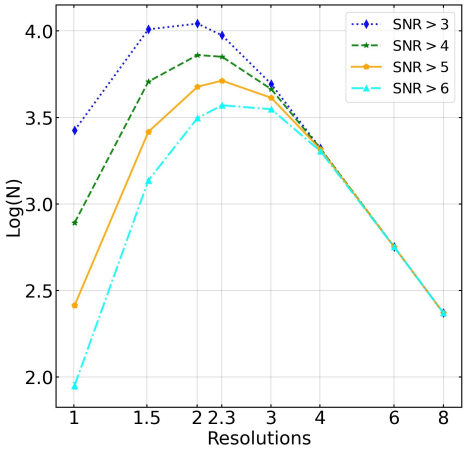
$$\sigma_{rms} = \frac{T_{sys}}{G\sqrt{2N_B\,\Delta t\,\Delta\nu_{ch}}}\,,\quad S_v \approx \frac{\beta(\theta)}{(2.36\times 10^5\,W_{20})}\frac{M_{HI}\,(1+z)}{D_L^2}$$



MeerKAT's 25 hrs direct detections: 30 Fields



ASKAP's 8 hrs direct detections: 15 Fields

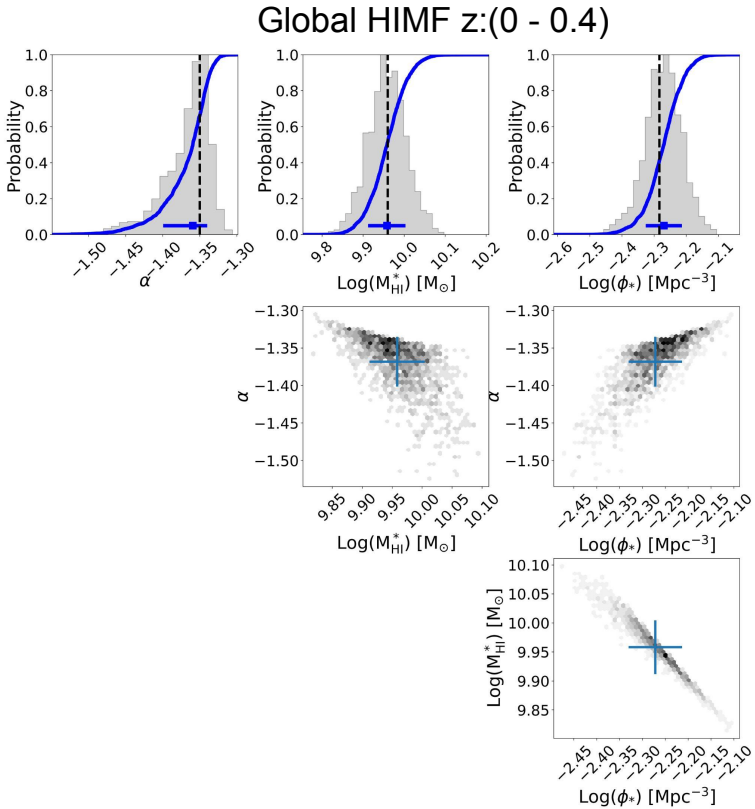


MeerKAT's resolution map: 30 Fields

Results:Constrain on HIMF

$$\phi(\mathrm{M_{HI}}) = \phi^* \left(\frac{\mathrm{M_{HI}}}{\mathrm{M^*_{HI}}}\right)^{\alpha+1} \exp\left(\frac{-\mathrm{M_{HI}}}{\mathrm{M^*_{HI}}}\right)$$

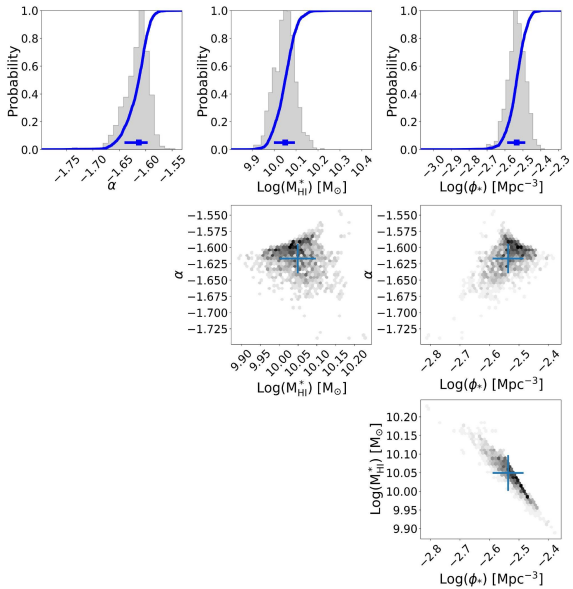
- Number of direct detection, stacked HI-mass and mean HI mass are used as mock observables.
- We assume models for each mock observable e.g. No. of direct detection Ndd given below.
- We used **PyMultinest** to estimate posterior probability distribution for HI mass function parameters.
- We found that with mock observations, using MeerKAT sensitivity , HIMF can be retrieved very well.



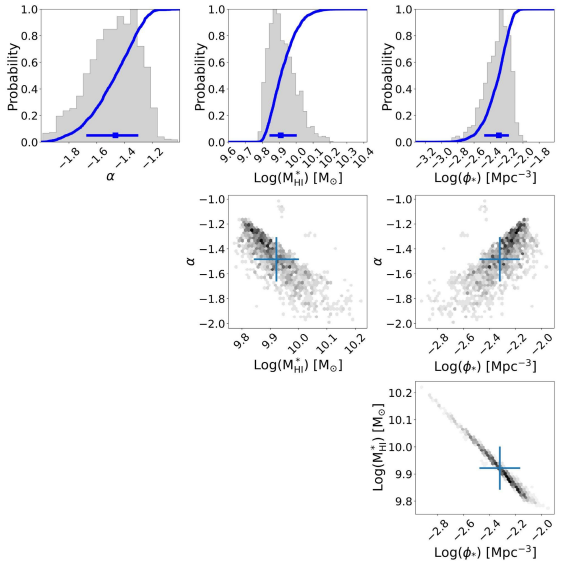
$$\mathrm{N_{dd}} = \omega \mathrm{D_{H_0}} \int_{z1}^{z2} \frac{\mathrm{D_C^2(z)dz}}{\mathrm{E(z)}} \int_{\mathrm{M_{HI}^{low}(z)}}^{\mathrm{M_{HI}^{high}(z)}} \phi(\mathrm{M_{HI}}) \mathrm{d}[\log_{10}(\mathrm{M_{HI}})] \int_0^{\mathrm{i^{high}(M_{HI},z)}} \sin(\mathbf{i})\mathbf{di}$$

Results:Constrain on HIMF with z

HIMF at z:(0 - 0.2)



HIMF at z:(0.2 - 0.4)



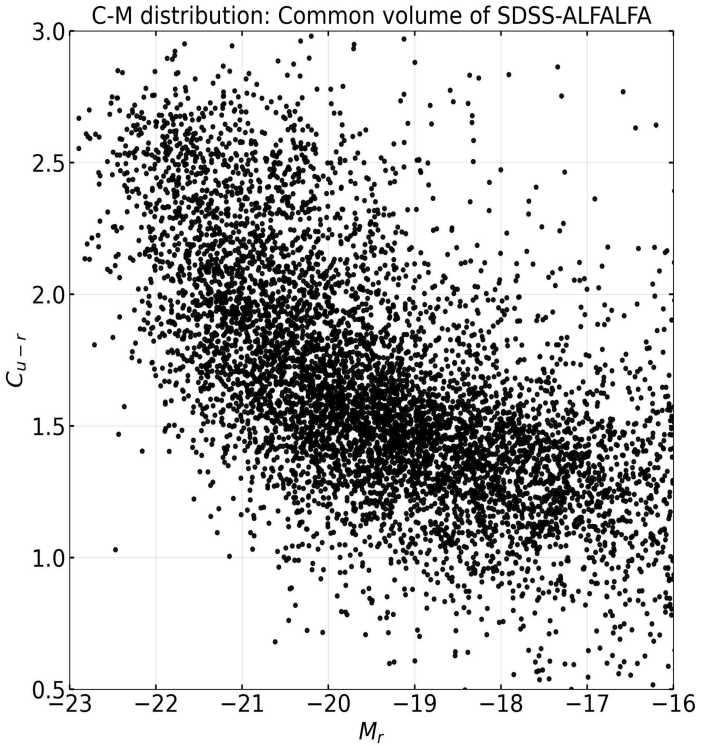
- The redshift evolution of HIMF can be studied with mock observation. We assume no evolution in Omega HI with redshift to constrain the HIMF.
- We also plan to do this exercise for different color-magnitude combination in order to explore, How does the HIMF behave with optical properties ?

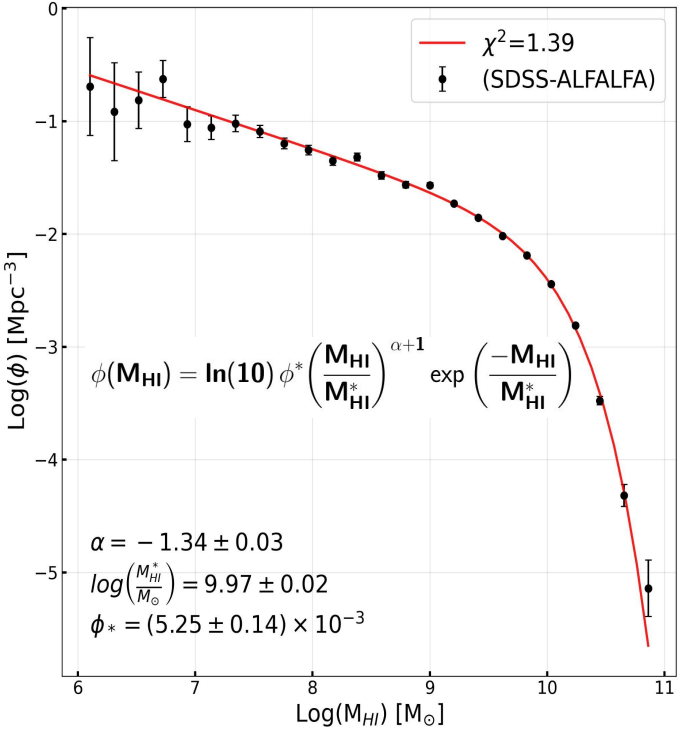
Summary and Take away

- We simulate observations for two HI-surveys: MIGHTEE-HI and WALLABY.
- Our method of generating mock catalog is simple and enables us to simulate low HI mass at higher redshift.
- Our mocks provide HI and optical properties of galaxy to understand their evolution.
- We predict the **number of direct detection** , **average stacked HI mass** and **median HI mass** of direct detection.
- Stacking, conditional HIMF will provide a bridge b/w HI-properties and optical properties of galaxies.
- With the our HI-optical mock catalog, we constrain HIMF with redshift using very limited information. This can be used to generate priors for a full estimation of the mass function.
- We also plan to estimate color and magnitude dependent HIMF from mock observations.
- These simulations can help in designing the SKA future survey with optimal strategy and can guide us to do the different HI science/galaxy evolution with observed data.

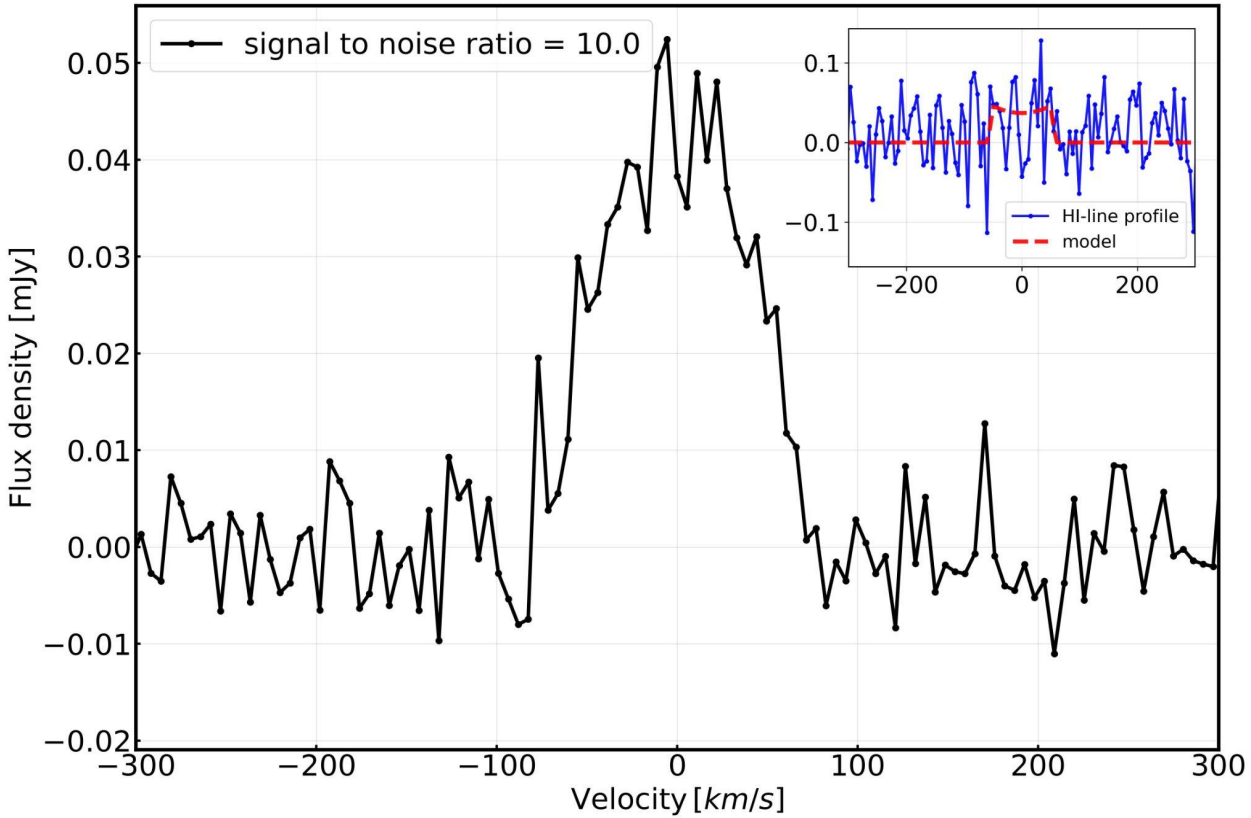
Supplementary

SDSS-ALFALFA common volume catalog and HIMF





Supplementary: HI-Stacking



Low SNR HI-stacking

Supplementary: sensitivity

- The effective number of baselines is estimated at a given declination for a baseline length.
- Galaxies locations and HI-masses taken to be randomly distributed controlled by HIMF and volume respectively.
- The size and velocity width of galaxies, estimated from HI mass and gas content respectively.
- The random inclination for each galaxy is added.

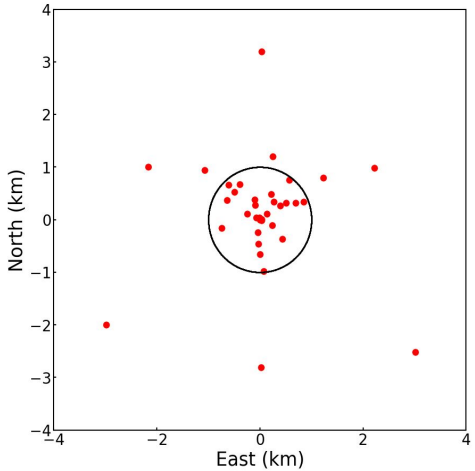
$$M_b = A\, V_f^4$$

$$W_{20} = 2\, V_f\, \sin i$$

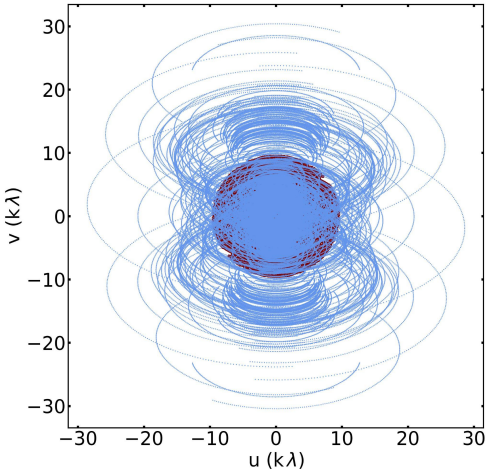
$$\log\left(\frac{D_{HI}}{kpc}\right) = 0.51\, \log\left(\frac{M_{HI}}{M_\odot}\right) - 3.32$$

$$d\nu_{ch} = \frac{W_{20}}{c}\,\frac{\nu_{HI}}{(1+z)}$$

$$\sigma_{rms} = \frac{T_{sys}}{G\sqrt{2N_B\,\Delta t\,\Delta\nu_{ch}}}\,,\quad S_v \approx \frac{\beta(\theta)}{(2.36\times 10^5\, W_{20})}\,\frac{M_{HI}\,(1+z)}{D_L^2}$$

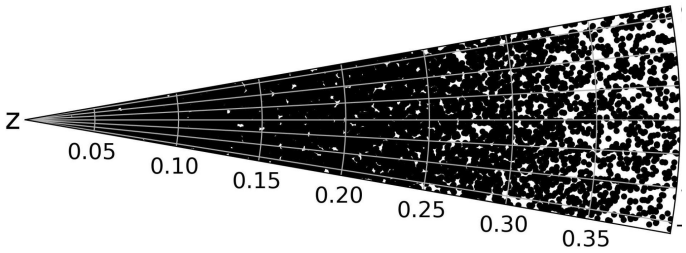


ASKAP antenna



ASKAP u-v coverage

Supplementary



Understanding galaxy evolution

(1) Understanding the role of gas ($HI+H_2$) in galaxies with optical properties. Observation at multi wavelengths.

(2) Measure/study the HIMF with cosmic time, optical properties and in different environment.

(3) Kinematic modelling of galaxies.

Supplementary

Parameter constraints and likelihood

$$N_{dd} = \int dV(z) \int \phi(M_{HI}) d(\log(M_{HI}))$$

$$\langle M_{HI} \rangle = \int dV(z) \int M_{HI} \phi(M_{HI}) d(\log(M_{HI}))$$

$$\chi^2_{\langle M_{HI} \rangle} = \sum_i^{bin} \left(\frac{\langle M_{HI} \rangle - \langle M_{HI} \rangle^{obs}}{\sigma} \right)^2$$